Smart Electricity Management System Using IoT with Prepaid Metering and Priority Based Load Switching

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Abstract

The rising global demand for electricity and the need for efficient energy utilization have accelerated the adoption of smart metering technologies, with smart energy meter deployment expected to exceed 1 billion units worldwide and energy losses due to inefficient consumption and theft accounting for nearly 20–25% in developing regions. Traditional energy meters rely on manual readings and postpaid billing systems, which often lead to inaccurate billing, delayed monitoring, energy wastage, and electricity theft. Furthermore, conventional systems lack real-time feedback, remote accessibility, and prioritized load control, reducing efficiency and user awareness. To address these challenges, the proposed IoT-based smart prepaid energy meter with prioritized load switching utilizes the ESP32 microcontroller to enable an intelligent and automated energy management system. The system continuously monitors electricity consumption and transmits real-time data to a centralized IoT platform for remote access and analysis. It incorporates a prepaid billing mechanism where users can monitor their balance and receive alerts when consumption approaches predefined thresholds. A prioritized load switching feature ensures that critical loads remain operational while non-essential loads are automatically disconnected during low balance conditions. Remote control capabilities allow users and providers to manage loads efficiently, while automated alerts and additional charge mechanisms enhance billing transparency. This solution improves energy efficiency, reduces losses, promotes sustainable consumption, and supports the development of smart and reliable power distribution systems.

Keywords: Energy Monitoring, ESP32, Internet of Things, Load Management, Prepaid Energy Meter, Prioritized Load Switching, Smart Grid, Smart Metering, Threshold Alert System.

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1. Introduction

The increasing global demand for electricity and the need for efficient energy utilization have significantly accelerated the adoption of smart metering technologies. It is estimated that smart energy meter deployment will exceed 1 billion units worldwide, reflecting a major transition toward intelligent power management systems. In developing regions,

energy losses due to inefficient consumption and electricity theft account for nearly 20–25% of total generated power, posing serious economic and operational challenges. Additionally, the integration of Internet of Things (IoT) technologies in energy systems is growing at a rate of over 19% annually, enabling real-time monitoring, data-driven decision-making, and improved grid efficiency. In environments such as residential buildings, commercial complexes, smart cities, and industrial facilities, there is a critical need for systems that provide accurate energy tracking, automated billing, and intelligent load management to ensure optimal power utilization.

Problem Statement: Traditional energy metering systems rely heavily on manual readings and conventional postpaid billing methods. These systems lack real-time monitoring capabilities, often resulting in delayed data collection and inaccurate billing. Consumers are typically unaware of their real-time energy usage, which leads to inefficient consumption patterns and higher electricity costs. Furthermore, conventional meters do not support remote access or automated control, making it difficult for utility providers to monitor consumption or detect irregularities such as power theft. The absence of intelligent load management also prevents prioritization of critical appliances, reducing the overall efficiency and reliability of power distribution systems.

Motivation: In real-time scenarios, these limitations result in several critical challenges affecting both consumers and utility providers. Delayed monitoring and billing can lead to unexpected high electricity bills and poor energy management, while lack of theft detection contributes to significant revenue losses. The absence of real-time alerts and feedback prevents users from making informed decisions about their energy usage. Additionally, without prioritized load control, essential devices may lose power during critical situations, affecting safety and productivity. These challenges highlight the need for an intelligent, IoT-based solution capable of real-time energy monitoring, prepaid billing, and automated load management, ensuring improved efficiency, transparency, and sustainability in modern power systems.

2. Literature Survey

Kheaksong et al. [7] proposed a packet transfer mechanism based on Device Language Message Specification/Companion Specification for Energy Metering (DLMS/COSEM) standards for smart grid communication. Park et al. [8] proposed a data interworking model for harmonizing smart metering protocols in Internet of Things (IoT)-based Advanced Metering Infrastructure (AMI) systems.

The authors in [9] proposed the IEEE 2030-2011 standard framework for smart grid interoperability, integrating energy technology and information technology operations within electric power systems. Zhou et al. [10] proposed scalable distributed communication architectures to support Advanced Metering Infrastructure in smart grids. The system enhanced reliability and scalability through decentralized communication models.

Abrahamsen et al. [11] proposed a comprehensive survey of communication technologies for smart grid applications, analyzing wired and wireless solutions for data transmission. Soares Ascenção et al. [12] proposed a literature review on smart water management systems, focusing on IoT-based monitoring, control, and optimization techniques.

Okoli et al. [13] proposed a framework for building smart water cities using IoT technologies, emphasizing system architecture, applications, and future directions. Ancillotti et al. [14] proposed an analysis of communication systems in smart grids, focusing on architectures, technical solutions, and research challenges. Wei et al. [15] proposed an analysis of integration and

development pathways for smart grid technologies, focusing on technological advancements, policy frameworks, and application challenges.

Uribe-Pérez et al. [16] proposed a state-of-the-art review of smart metering technologies in electricity grids, analyzing system architectures, communication protocols, and emerging trends. Porwal et al. [17] proposed a leakage detection and location prediction system in smart water grids using Support Vector Machine (SVM) classification.

Wang et al. [18] proposed a deep learning-based approach for identifying socio-demographic information from smart meter data using advanced data analytics techniques. Wang et al. [19] proposed a review of smart meter data analytics, covering applications, methodologies, and challenges in smart grid systems. The study analyzed data-driven techniques for improving grid performance. The work lacked experimental benchmarking.

Kappagantu et al. [20] proposed an analysis of challenges and issues in smart grid implementation with a focus on the Indian scenario. Kanellopoulos et al. [21] proposed a review of networking architectures and protocols for IoT applications in smart cities, focusing on recent developments and system design considerations.

3. Proposed System

Figure 1 illustrates the architecture of an IoT-based smart energy monitoring and control system built around the ESP32. The system integrates an energy meter, keypad input, and regulated power supply as input modules, while output modules include an LCD display, relay-controlled loads, buzzer alerts, and Wi-Fi-based cloud communication. The ESP32 processes real-time energy consumption data, displays it locally, and transmits it to a cloud server for remote monitoring via a mobile website. Additionally, the system implements intelligent alert mechanisms and load control features, ensuring efficient and user-friendly energy management.

Step 1: Power Supply Unit: The regulated power supply provides stable DC voltage to the ESP32 and all connected components, ensuring reliable and uninterrupted system operation. It converts AC input into regulated DC output suitable for electronic circuits.

Step 2: Energy Meter Input: The energy meter continuously measures real-time electricity consumption and sends the data to the ESP32 microcontroller. This enables accurate monitoring of power usage without manual intervention.

Step 3: User Input via Keypad: The keypad allows users to interact with the system, such as setting consumption limits, resetting alerts, or configuring system parameters. This provides flexibility and user control.

Step 4: Data Processing by ESP32: The ESP32 acts as the central processing unit, analyzing energy consumption data, comparing it with predefined thresholds, and making decisions for alerts and load control.

Step 5: LCD Display Output: The LCD displays real-time energy consumption data, system status, and alerts. This helps users monitor electricity usage locally and take immediate action if needed.

Step 6: Relay-Based Load Control: Relay modules (R1, R2, R3) control multiple electrical loads (L1, L2, L3). The ESP32 can automatically or manually switch loads ON/OFF based on energy consumption or user commands.

Step 7: Buzzer Alert Mechanism: When energy consumption exceeds a predefined limit, the buzzer is activated to alert the user. The alert continues for additional excess usage, reinforcing awareness and encouraging controlled consumption.

Step 8: Wi-Fi and Cloud Integration: The ESP32 uses built-in Wi-Fi to transmit data to a cloud server. This allows users to monitor energy usage remotely through a mobile website, access historical data, and receive alerts in real time.

Step 9: Remote Monitoring via Mobile Website: Through cloud connectivity, users can view energy consumption, control loads, and manage alerts using a mobile interface. This enhances convenience and enables smart energy management.

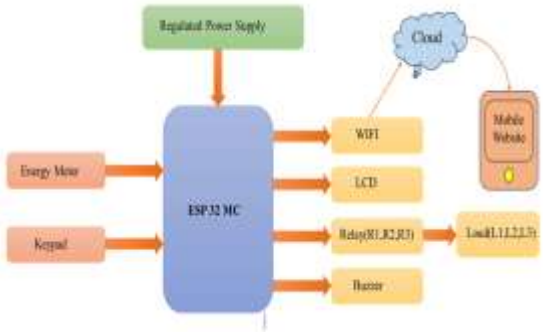

Figure 1. IoT-Based Smart Energy Monitoring System Using ESP32.

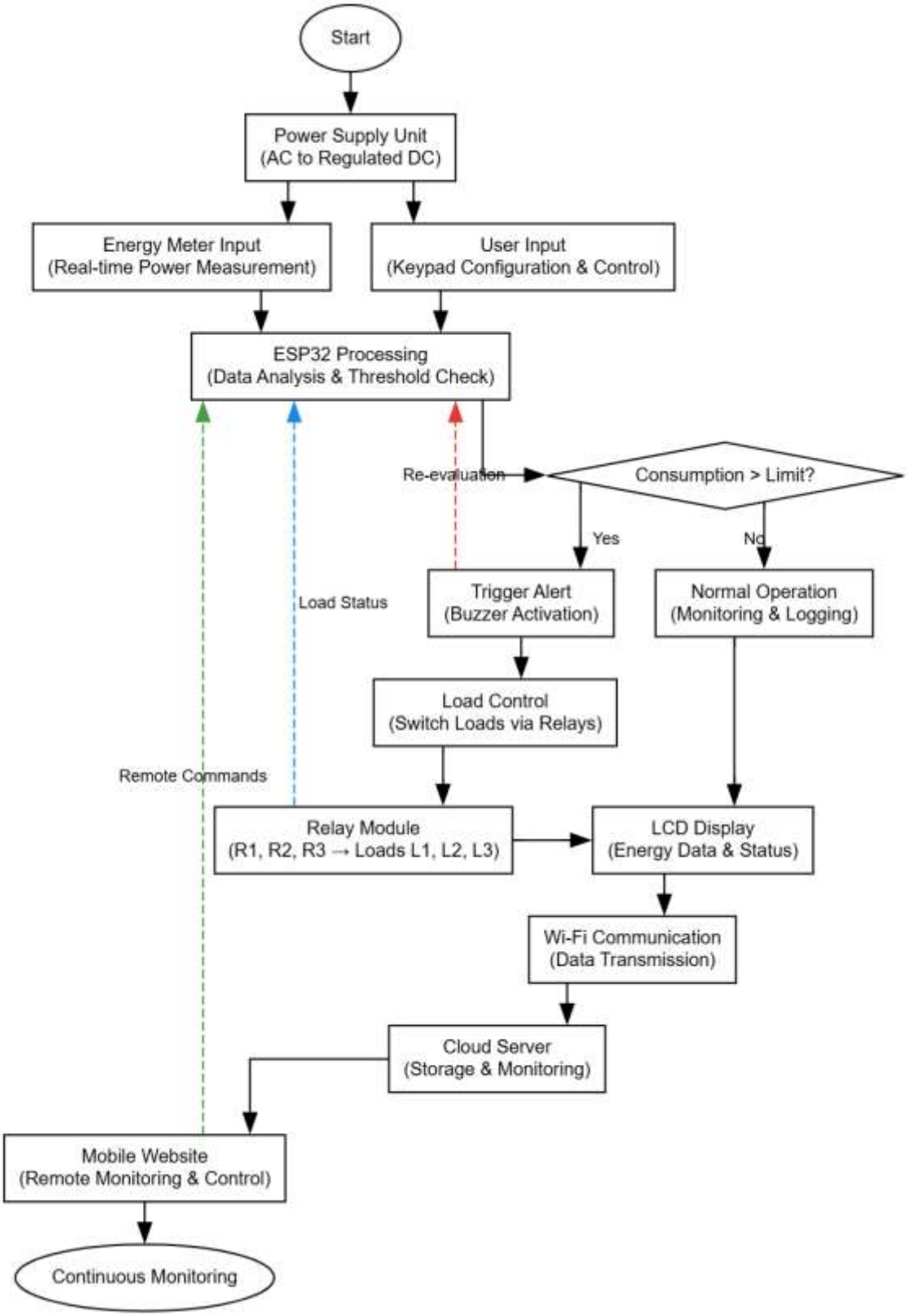

Figure 2. Proposed System Working Procedure.

Figure 2 represents a system built around the ESP32 microcontroller for energy monitoring and load control. A regulated power supply ensures stable operation of the ESP32 and connected components. The system receives input from an energy meter, which measures power consumption, and a keypad that allows user interaction.

The ESP32 processes data and communicates with different output devices. A WiFi module enables cloud integration, allowing real-time data access and control via a mobile website. The LCD provides a local display of system information. A relay module controls multiple loads, switching them on or off based on commands from the microcontroller. A buzzer is included to provide alerts or notifications.

Through cloud connectivity, users can monitor and control the system remotely using a mobile website, ensuring efficient energy management. The system integrates both local and remote-control functionalities for better usability and monitoring.

4. Results and Discussion

Figure 3 shows the complete hardware setup of the IoT-based smart prepaid energy meter system mounted on a baseboard. It includes the main energy meter unit for measuring electrical consumption, an ESP32 microcontroller board for processing and IoT communication, a relay module for load control, and a 16×2 LCD for displaying real-time parameters. The interconnected wiring demonstrates the integration of sensing, control, and communication modules, enabling automated energy monitoring, prepaid billing, and intelligent load switching.

Figure 4 illustrates the system in operational condition, where the energy meter is actively measuring power usage and the ESP32-based control unit is powered ON. The relay module is energized, indicating load switching functionality, while LEDs and circuit components show active current flow. The setup highlights real-time processing and control of electrical loads based on prepaid balance and system logic.

Figure 5 presents a close-up view of the 16×2 LCD display, which shows key electrical parameters such as voltage (V), current or units (U), and status values. These readings are continuously updated by the ESP32 controller, providing users with real-time feedback on energy consumption and remaining prepaid balance, thereby enhancing user awareness and energy management.

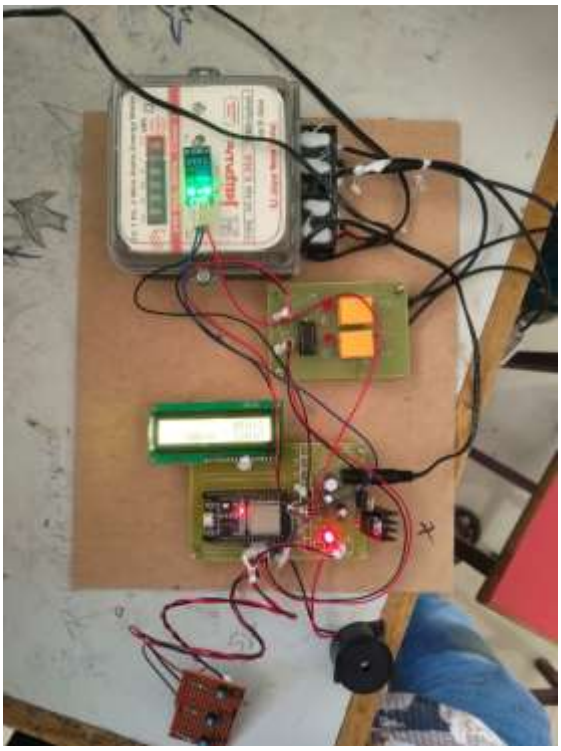

Figure 3. Overall Hardware Prototype of IoT-Based Smart Prepaid Energy Meter.

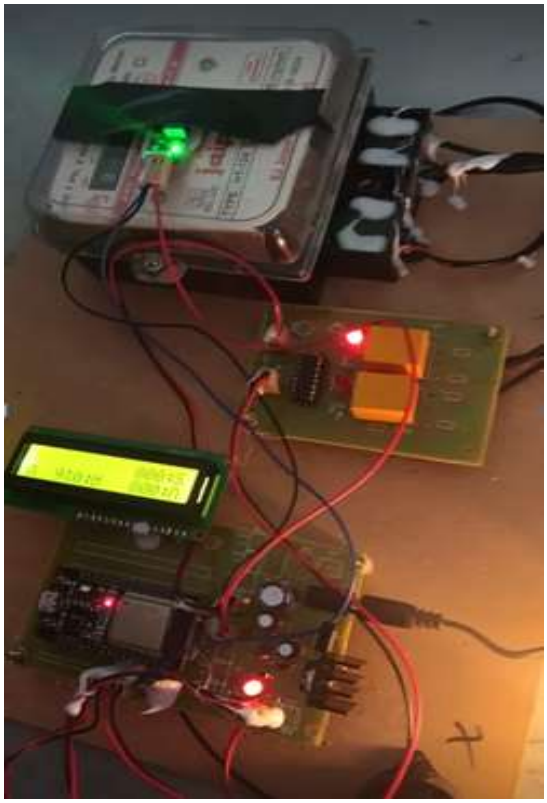

Figure 4. Active System Operation with Power and Load Control.

Figure 6 focuses on the energy meter interface module connected to the IoT system, where sensor data is captured and transmitted to the ESP32. The module enables accurate measurement of electrical parameters and supports remote monitoring through IoT platforms. It plays a critical role in enabling smart billing, data logging, and prioritized load control in the overall system.

Figure 5. LCD Display Showing Electrical Parameters

Figure 6: IoT-Enabled Measurement and Monitoring Unit

5. Conclusion

The proposed system collectively demonstrates the design, implementation, and real-time operation of the IoT-based smart prepaid energy meter system, highlighting its effectiveness in modern energy management. The complete hardware setup illustrates seamless integration of the energy meter, ESP32 microcontroller, relay module, and LCD display, forming a cohesive system for monitoring, control, and communication. The operational view confirms the system's ability to actively measure power consumption and perform intelligent load switching based on prepaid balance, ensuring efficient energy utilization. The LCD interface provides real-time visibility of key electrical parameters, enhancing user awareness and enabling better consumption control. Furthermore, the energy meter interface module ensures accurate data acquisition and supports IoT-based remote monitoring, enabling smart billing and data-driven decision-making. Finally, the system proves to be a reliable, automated, and user-friendly solution that reduces energy wastage, supports prepaid energy management, and contributes to the development of smart and sustainable power distribution systems.

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